

8th International Conference on Photonic Technologies LANE 2014

Undercuts in Laser Arc Hybrid Welding

Jan Frostevarg^{a,*}, Alexander F.H. Kaplan^a

^a*Luleå University of Technology, Luleå 97 187, Sweden*

Abstract

Undercuts are usually an imperfection in welding that either continuously or sporadically form, especially when welding at high speed. Efforts, usually lowering the welding speed or overfilling, are applied to avoid undercuts as they can significantly lower the fatigue properties of the welded workpiece. Undercut formation is complex and occurs by various means, mainly based on temperature and melt flow mechanisms. When having two power sources as in laser arc hybrid welding, the melt flow can be tailored to suppress undercut formation. This can be done e.g. by narrowing the width of the gouge or by optimum positioning of the power sources relative to each other. The present paper shows and explains the main reasons of various types of undercut formation. By following the herein generated guidelines, the critical welding speed during laser arc hybrid welding can be further increased, free of undercuts.

© 2014 Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: Undercut; Laser; Arc; Hybrid; Welding; Shapes; Mapping

1. Introduction

This study aims at creating a survey and at systematically categorizing different types and origins of the undercut weld imperfection in Laser Hybrid Arc Welding (LAHW), Bagger and Flemming (2005), with the leading arc configuration and using a 1 μm wavelength laser. Already reported undercuts in Laser Beam Welding (LBW) and Gas Metal Arc Welding (GMAW) found in literature are also here presented and categorized. Undercut reduces the mechanical properties of welds. If not kept to a minimum, undercut may severely reduce the fatigue properties of the entire welded construction Alam, et al (2010), Bell, et al (1989), Nguyen and Wahab (1998), Otegui, et al (1989).

* Corresponding author. Tel.: +46-920-49-1675 ; fax: +46-920-49-1399 .

E-mail address: jan.frostevarg@ltu.se

Figure 1 illustrates the LAHW process while Fig. 2 illustrates designations and imperfections of an LAHW weld, including undercuts. Welding standards, such as the one for LAHW (ISO/FDIS 12932), specifies typical tolerance limits for occurring undercuts but not how to prevent them. In order to prevent undercut formation in arc welding, the arc generated gouge needs to be filled, Mendez and Eagar (2003). A typical counter measure is to add more material to the process, overfilling the weld and forming a high reinforcement, neither esthetical nor cost-effective.

As welding speed has increased over the years, e.g. by LBW and LAHW, undercuts have become a more severe issue, Kaplan, et al (2007). In fusion welding the speed is often limited by the occurrence of undercuts, coupled with high power the speed can be further limited by other imperfections such as humping, Nguyen, et al (2006), Soderstrom and Mendez (2006). Undercut formation is generated by solidification (dependent on heat conduction) and melt flows, which is dependent on chemistry- and temperature-dependent viscosity and surface tension. Surface tension typically decreases with higher temperatures, negatively affecting adhesion to the solid metal, Mendez and Eagar (2003). Welding on mill scale is known to cause more/larger initial flaws and poorer fatigue behavior (usually due to undercuts), compared to having the mill scale removed, Nguyen and Wahab (1996a). The mill scale usually consists of Fe and FeO in the layer close to the base metal, accompanied by Fe_2O_3 and Fe_3O_4 in the upper layer, Legodi and de Waal (2007).

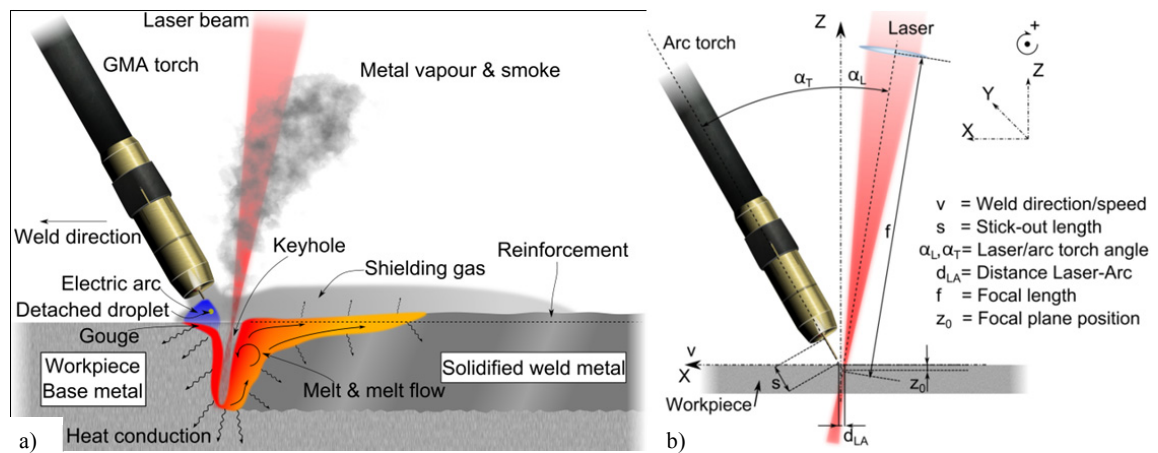


Fig. 1. (a) Illustration of laser arc hybrid welding; (b) geometrical setup.

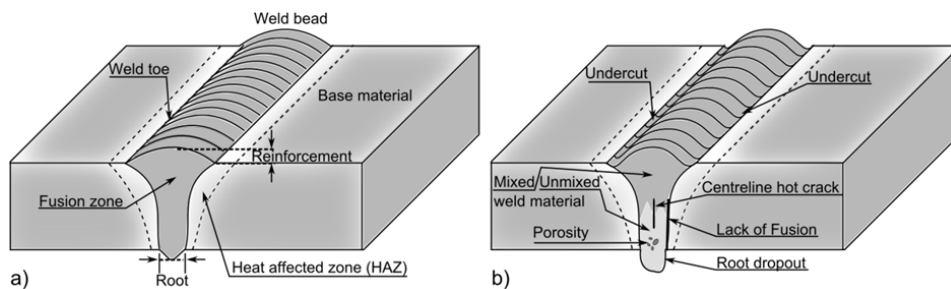


Fig. 2. LAHW crosscut (a) designations; (b) common weld imperfections.

1.1. Undercuts in Laser Beam Welding

Figure 3 shows illustrated LBW generated undercuts found in literature. Here, three different types of undercuts are presented where each has different formation causes. The curved undercut is increasingly formed at higher welding speeds (using the same line energy), Eriksson, et al (2011). Due to lowered wetting, where the temperature gradients between the melt and solid are believed to be the key, factor Pengfei, et al (2011). The rounded bottom

undercut (underfill) occurs when having the laser at an unfavourable focal position, probably causing to excess evaporation, Karlsson, et al (2010). The central line undercut occurs when the base material has high magnesium content, Zhu, et al (2005).

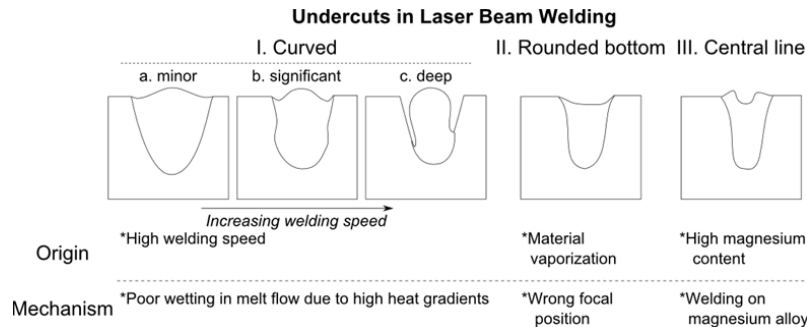


Fig. 3. Different types of undercuts in laser beam welding.

1.2. Undercuts in Gas Metal Arc Welding

For electric arc welding Mendez and Eagar (2003) interprets (direct observations are still missing) the solidified melt as follows: High pressure (by high arc current) from the electric arc depresses the weld pool surface so that only a thin metal film remains. Premature solidification of this thin layer stops the wetting of the side of the weld bead, causing undercuts. However, according to Nguyen, et al (2006) review, is model emphasizes only the thin film at the front while the significant role of the rim in transporting liquid metal to the trailing region is ignored. Despite several theories on the melt film flow the exact undercut formation mechanism is still unclear. Several techniques have been demonstrated (but not always fully documented) to be effective in suppressing undercuts by slowing the backward flow of the liquid.

From literature three different undercut types were found and distinguished for GMAW, illustrated in Fig. 4. The double sided Curved undercut that occurs during high speed welding (strong arc), mainly due to wetting problems Mendez and Eagar (2003), Nguyen, et al (2006). The single sided Curved undercut occurs when the arc is misaligned, thus improperly filling the groove. The Crack like undercut is most likely due to a diluted surface prior to welding, causing poor wetting properties, Nguyen and Wahab (1996a).

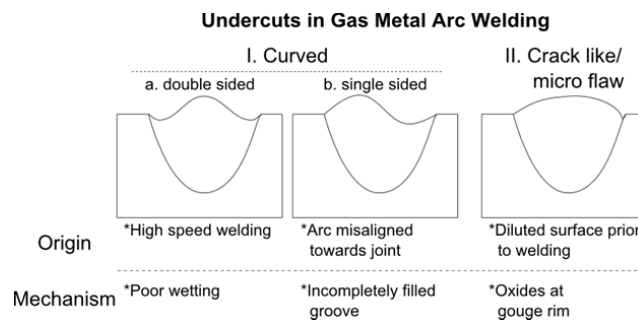


Fig. 4. Different types of undercuts in gas metal arc welding.

2. Methodology

From literature, various undercuts having different shapes and causes can be found for butt joint welding in steel, here systematically categorized for LBW and GMA. The same can be done for LAHW, but findings in literature are scarce. By collecting results from various experiments, systematic categorization and mapping of arc leading

LAHW undercut types can be made. In particular, as far as understood the weld parameter or material origins and the resulting physical mechanisms responsible for the respective undercut types are added in the undercut map. The map is most likely not here completed and later findings may be added into the map. Undercut formation mechanisms need to be understood and researched in order to produce guidelines for suppressing or avoiding them.

The undercuts are here post-weld analysed by various means; using macrographs, SEM, EDX and surface scanning. The welds were also observed by High Speed Imaging (HSI), which helped in post-weld analysis to reveal undercut formation mechanisms.

In all experiments, nearly the same laser and arc setup were used, illustrated in Fig. 1b. The varying experimental parameters can be found in Table 1, where the samples are already ordered in undercut types. The work piece steel material used was Domex 420 MC, EN-10149-2-S420 MC with milled (I, IIa) or laser cut surfaces (others) in a butt joint configuration. All samples were fully penetrated. Only Ia had the mill scale remaining prior to welding. The laser and optics used where a 15 kW Yb:fibre laser (IPG, YLR 15000) with a fibre diameter of 200 μm operated in CW mode using optics with 300 mm focal length, creating a focal spot diameter of 400 μm . The process was shielded by a gas with a mixture of 92% Ar and 8% CO_2 . Two different GMA equipments were used: The first was an ESAB Aristo LUD450W with wire feed unit MEK 44C, operating in standard or pulsed mode. The second was a Fronius TPS4000 VMT Remote with a VR7000 wire feeder and a Robacta drive, operated in either standard, pulsed or CMT arc mode. The arc was positioned in leading position, using an AWS A5.18 ER 70S-6 $\phi=1.2$ mm filler wire with 18 mm stickout. The laser and the arc where tilted with 7° and $\sim 28^\circ$ inclination, respectively.

Table 1. Main welding parameters varied for the studied undercut types I-VI (Z_0 focal plane position, D_{LA} distance laser-arc).

Undercut type	Plate thickness (mm)	Welding speed (m/min)	Arc mode	Arc power (kW)	Wire feed rate (m/min)	Laser power (kW)	Z_0 (mm)	D_{LA} (mm)	Gap size (mm)
I	10	2.1	Pulsed	10.5	12	8	-5	3	0.3
IIa	10	2.1	Pulsed	10.5	12	8	-5	3	0.3
IIb	7	2	CMT	5	8.3	6	-3	3	0
III	7	2.5	CMT	5	8.3	7	-3	3	0
IVa	7	2.5	CMT	5	8.3	8	-3	3	0.4
IVb	7	2	CMT	3.2	6.4	7	-3	3	0
V	7	2	Standard	7.7	8.3	6	-3	3	0
VI	7	5	Pulsed	5.1	8	8	-3	2	0

3. Undercuts in laser arc hybrid welding

Undercuts are formed differently depending on the process and surface conditions. In LAHW, undercuts may be categorized into two groups, continuous and occasional/irregular/alternating. Figure 5 gives a survey of the here identified types of undercut shapes found in LAHW, including the possible causes and mechanisms. Continuous

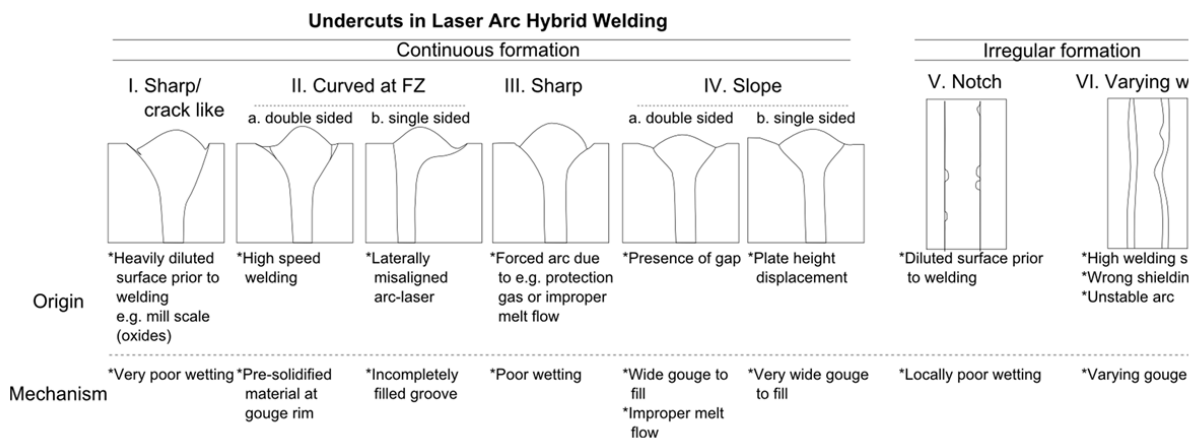


Fig. 5. Different types of undercuts in laser arc hybrid welding, I-IV cross section and V-VI top view, and causes, mechanisms.

undercuts are mostly caused by improper process parameters, setup or methodology, while the irregular undercuts are caused by process instability. Undercuts formed with arc leading LAHW are mostly determined by the arc created gouge and the melt flow assisted by the keyhole generated by the laser. Undercuts formed in LAHW are therefore more similar to the ones formed in GMAW, rather than LBW. Possible undercuts in LAHW with trailing arc are based on different conditions not treated here. In LAHW with leading arc, the gouge is usually wider than the laser generated melt pool. The outer most region at the surface of the gouge is susceptible to premature solidification and it is here that undercut formation is initiated and grows. In the HSI in Fig. 6 the undercut formation region in LAHW is marked. The mechanisms in this area need to be understood and optimized.

Followed from here, each category of undercuts in Fig. 5 is described by an experimental case and also discussed.

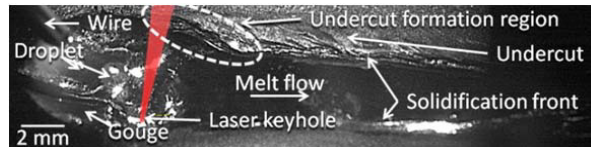


Fig. 6. Frame from high speed imaging, with annotations.

3.1. Type I & II

Formation of these two types of undercut are divided here in two cases; case I with surface oxides (mill scale) and case II with the surface oxides removed. Formation mechanisms are likely very similar to the formation of GMA undercut classes Ia & II, Fig. 4. Figure 7 shows macrographs where differences in geometry details can be seen. Abbreviations: BM Base Material, HAZ Heat Affected Zone, MBM Melted Base Material, PMBM Partially Melted Base Material, FZ Fusion Zone (contains ~32% wire material, balance is BM), MSO Melted Surface Oxides. The chemical composition of various interesting locations of Fig. 7 is shown in Table 2.

In case I the MBM starts clearly beneath the original surface level, has a sharp angle and a sharp bottomed inclusion filled with oxides, effectively acting as a lack of fusion defect, Fig. 7g. Figure 7h shows the 10-20 μm thick mill scale, consisting of iron oxides. In case II the MBM has a wavy profile and starts near the surface level. While the PMBM starts at the surface level in case II, it starts lower and is thinner in case I.

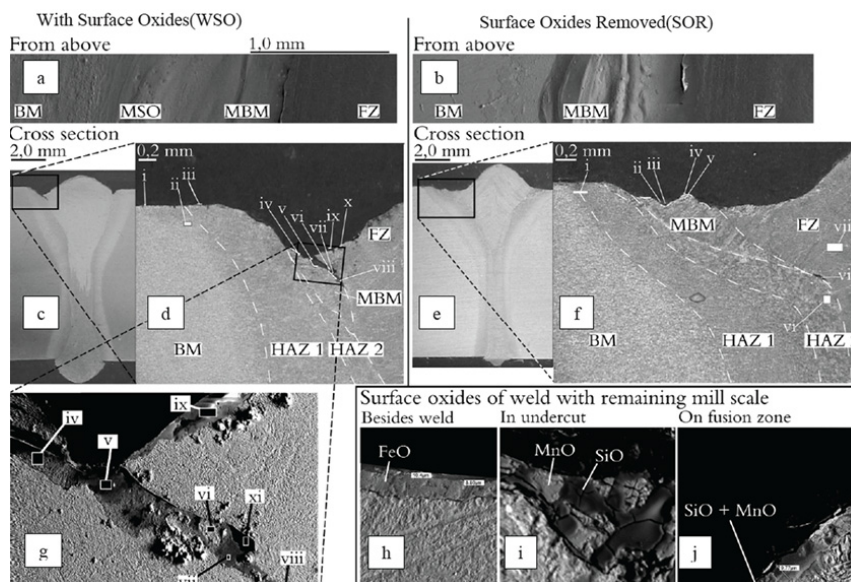


Fig. 7. (a) and (b) shows the top view for undercut type I (WSO) and IIa (SOR). Macrographs are shown in (c)-(f), with enlarged SEM image (g) of the lack of fusion; (h)-(j) shows surface oxides.

The surface oxides at the heated and melted regions also contain Si-oxides, beside the Fe-oxides. In addition, for case I much MnO was found in the LoF-region (as a separate phase beside SiO, see Fig. 7(i)). In case II no MnO can be found except in a few cavities or grooves, Karlsson, et al (2011), Norman, et al (2011).

Figure 8 shows HSI of the melt pool for the two cases. The overall melt flow is complex and described in Karlsson, et al (2011). The leading arc pushes away the melt, creating a gouge that obviously oxidizes, see Fig. 7. The important difference observed is that in case II some of the MBM adheres near the top surface, which solidifies and the main melt flow later adheres to. In contrast, in case I the liquid is forced up on the oxidized wall but glides down again, shown in the sequence Fig. 8c-e) and illustrated in Fig. 8f). This mechanism causes the Lack of Fusion and undercut geometry of Fig. 7. At the rear part of the gouge the outer region of the melt resolidifies, forming the corresponding undercut, particularly in the critical region highlighted in Fig. 8f).

Table 2: Chemical composition at locations i-xi in Fig. 1 (balance is mainly carbon).

No.	I: With surface oxides (at-%)				II: Removed surface oxides (at-%)			
	O	Si	Mn	Fe	O	Si	Mn	Fe
i	13		1.0	82		0.3	1.2	97
ii			1.5	97	7.6		20	72
iii	17	11		71	36	37	3.5	23
iv	9.5	4.1	30	55	33	29		8.5
v	14	8.9	15	60			1.4	97
vi		0.3	0.7	96			1.6	96
vii	12	7.6	19	57	8.5	3.0	53	29
viii	8.8	3.4	28	58		0.2	1.8	95
ix	22	13	39	20				
x ⁺	8.1	0.3		1.8				
xi	8.1	0.9	1.5	88				
*		.06	1.5	98				
**		2.0	1.7	96				

+ = Carbon 89.9 %

* = BM

** = wire

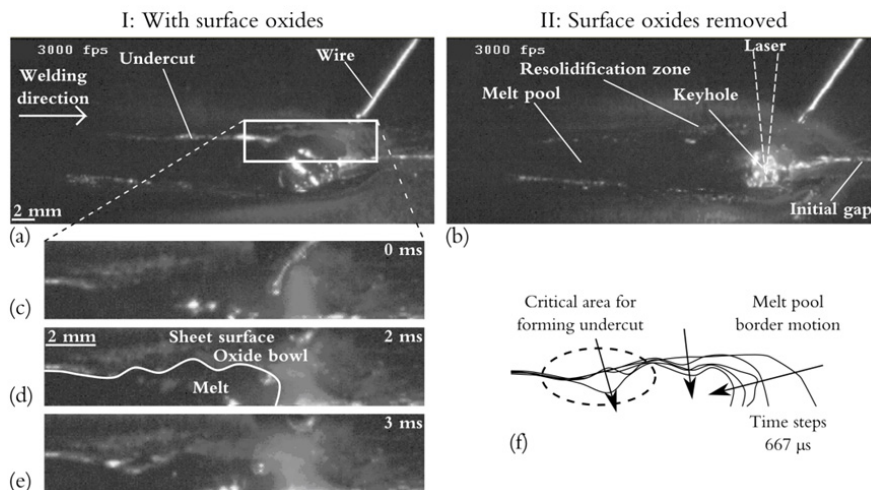


Fig. 8. Image sequence and illustration to visualize the melt pool and flow for undercut types (a,c-f) I; (b) IIa.,

When the laser and arc are laterally misaligned, the central melt flow is behind the laser. This can effectively both cause and prevent undercut formation on the far and close side to the solidification front, respectively, Fig. 9a-b) Frostevarg, et al (2013) demonstrates type IIb, as being curved type.

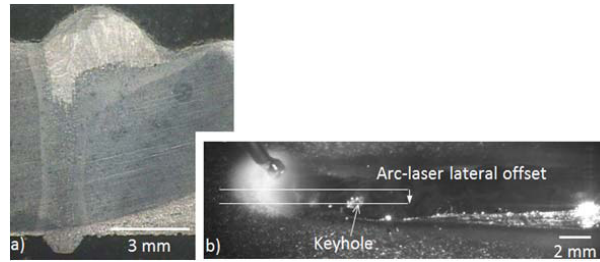


Fig. 9. Curved -single sided undercut, type IIb (a) cross section; (b) frame from high speed imaging.

3.2. Type III - Sharp

In the case when the gouge is deep and narrow due to the arc being narrowed by e.g. shielding gas (e.g. high CO₂ content), the strong arc pushes the melt of the gouge walls, not leaving any MBM for the main melt flow to adhere to. The angles of the bead in the gouge gets sharp, which yields worse fatigue properties, Fig. 10a-b). This shape can also be achieved by welding at high speed, which increases the temperature gradients of melt and solid and thus lowering wetting, increasing the angle at which the melt touches the surface.

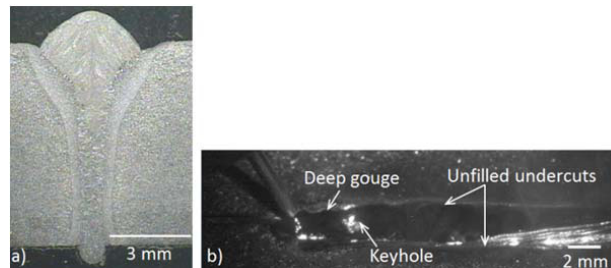


Fig. 10. Example of sharp undercut, type III (a) cross section and; (b) frame from high speed imaging.

3.3. Type IVa & IVb – Wide slope, double & single sided

In some cases, the arc creates a wide gouge which becomes very difficult to fill, Fig. 11a-b), e.g. in the presence of a gap. The mechanisms are similar to undercut type IIb, but the pressure of the arc is stronger so that there is no MBM for the main melt flow to adhere to. Higher wire feed rates would be needed, but this requires more power in the arc, consequently creating an even larger gouge. When the plates have height displacement, the arc melts more material from the material closer to the wire tip, also forming a wide slope in the gouge on that side of the weld, Fig. 11c-d), forming an undercutting region that is very difficult to fill, Lamas, et al (2013).

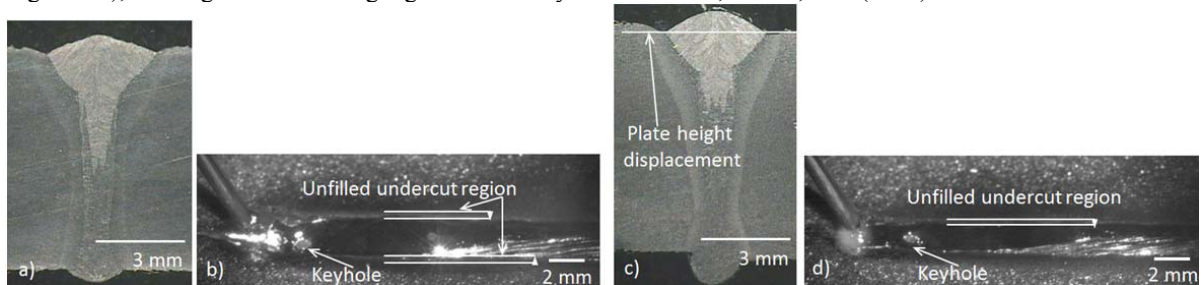


Fig. 11. Wide slope -double sided undercut, type IVa (a) cross section; (b) frame from high speed imaging. Wide slope -single sided undercut, type IVb (c) cross section; (d) frame from high speed imaging.

3.4. Type V– Notch

The notched undercut is formed at the end of the reach of the arc. Local conditions at the gouge rim causes low wetting, possibly exposing a spot of base metal. This area is not covered later by the melt flow due to surface tension forces, effectively keeping the spot open during solidification. These local conditions can e.g. be caused by dilutes on the work piece surface prior to welding. Figure 12 shows a cross section of an undercut notch and an image formation sequence.

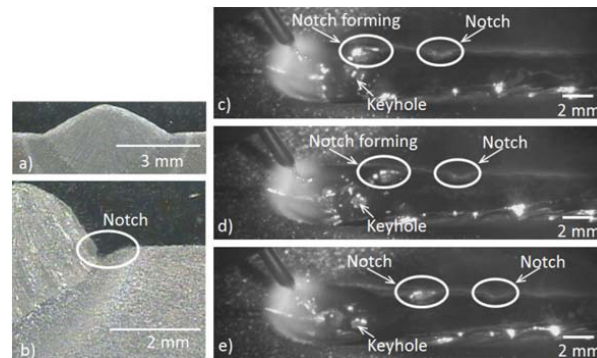


Fig. 12. Cross section (a) without and; (b) with notch undercut, type V; (c-e) image sequence showing notch formation.

3.5. Type VI - Varying width

More common and more severe than the undercut notch is when the arc is unstable. Arc instability means that the arc force, size and position on the workpiece varies, creating a gouge that varies in shape over the length of the weld, Fig. 13a-c. When the gouge alternates in shape, the melt flow and resolidification does the same, creating areas of excess bead reinforcement and undercuts, explained in Frostevarg, et al (2013). Causes of arc instability can be e.g. bad settings, resulting in uneven drop transfer or bad choice of shielding gas, Fig. 13d. Also, when welding at higher speeds, arc instability gets more noticeable since the arc has less time to “even out” the gouging area.

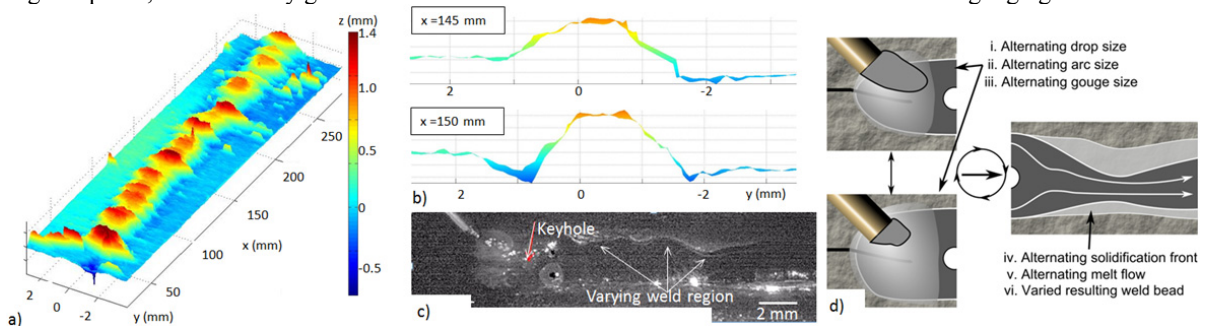


Fig. 13. (a) Scanned weld surface with varying undercut, type VI and (b) surface profiles at two locations to show variation (same colour scale); (c) image with a varying weld bead; (d) illustration of possible cause for instability.

4. Discussion

Undercuts form in various ways, but some general mechanisms and guidelines for undercut suppression in LAHW can be formulated, including the here presented categorization for LAHW into six types, I-VI, Fig. 5. These studies are comprehensive but of course not complete with respect to undercut types, causes, mechanisms and counter-measures. In both LBW and GMAW, welding speed is limited due to undercut formation (melt flow and temperature gradients), but LAHW has the advantage of multiple heat sources (arc and laser). These can be adapted

to counter the undercut formation and potentially increase the welding speed even further than LBW or GMAW alone, without undercuts. Very important is the undercut formation region marked in Fig. 6. If melt pool narrowing is prevented and the solidification front is V-shaped, undercutting is prevented. The melt needs to be able to wet the surface and adhere at the work piece base level.

Undercut formation criteria involves:

- Melt pool shape; gouge, transition at the laser keyhole position, melt pool tail
- Melt flow; viscosity, surface tension, positioning and pressure from heat sources
- Thermodynamics; temperature gradients, convection, heat input
- Chemistry; surface dilutes (e.g. mill scale), shielding gas

If not crucial, the simplest method to suppress undercut formation is to lower the welding speed, but there are other solutions. LAHW undercut type I and V can be avoided by removing oxides and cleaning the surface prior to welding. Type IIa, III, IVa,b can be suppressed by increasing wetting, changing the shape of the gouge and the melt flow. Type IIb and IVb are avoided by carefully placing the laser and arc in line and not having plate mismatch.

There are a number of measures that can be taken to improve the wetting and melt pool shape. Wetting could be improved by e.g. pre-heating the work piece prior to welding or choosing a more suitable shielding gas, El-Batahgy (1997), Sun, et al (2002), Tani, et al (2007). By making the gouge in front of the keyhole smaller should also make the undercut formation region smaller. This could be done by changing arc parameters, wire diameter or shielding gas. If the melt flow is proper, the melt gets longer time to sufficiently heat the sides of the undercut formation region to make the melt adhere to the surface. In LAHW, the melt flow could be altered by properly placing and inclining the heat sources such as to shape a favorable transition from the gouge to the laser-induced melt pool, Mendez and Eagar (2003). The distance between the laser and arc, D_{LA} , has also been shown to affect penetration depth, where the distance needs to be adapted depending on the arc current, Campana, et al (2007), Chen, et al (2006), Kutsuna and Chen (2003). An alternative could be to add a third heat source to counteract the backward flow of the melt, Staufer (2005), Tusek and Suban (1999), Wieschemann, et al (2003).

5. Conclusions

- Undercuts appear in different shapes, formed in various ways
- For butt joint welds, three different undercut types were identified in LBW, three in GMAW and here, six different types in arc leading LAHW
- Undercut types can be divided into continuous and irregular formation mechanisms
- Undercuts form in the critical undercutting region, which is where the melt flow narrows behind the arc generated gouge, i.e. the widest weld surface location. The following solidification front should be V-shaped along the length of the weld pool
- Increasing welding speed negatively affects wetting and arc stability

When mechanisms are known, the weld can be tailored to prevent undercut formation. Different strategies can be used to counter undercut formation:

- Chemically, by choosing a proper shielding gas to both improve arc stability and wetting
- Thermodynamically, by making temperature gradients more similar, by e.g. pre-heating or lowering the welding speed
- Mechanically, appropriate shape of the gouge and tailoring the melt flow in order to prevent formation of the critical undercut region and to promote a good solidification front

Acknowledgements

The authors gratefully acknowledge funding by the European Commission, programme FP7-RFCS, project HYBRO, no. RFSR-CT-2012-00024 and by VINNOVA – The Swedish Agency for Innovation Systems, programme FFI, project ROBUHYB, no. 2011-01782.

References

- Alam, MM, Barsoom,Z, Jonsén,P, Kaplan,AFH, Häggblad,HÅ, 2010. The influence of surface geometry and topography on the fatigue cracking behaviour of laser hybrid welded eccentric fillet joints, *Applied Surface Science* 256, 1936-1945.
- Bagger, C, Flemming,OO, 2005. Review of laser hybrid welding, *Journal of Laser Applications* 17, 2-13.
- Bell, R, Vosikovskiy,O, Bain,S, 1989. The significance of weld toe undercuts in the fatigue of steel plate T-joints, *International Journal of Fatigue* 11, 3-11.
- Campana, G, Fortunato,A, Ascari,A, Tani,G, Tomesani,L, 2007. The influence of arc transfer mode in hybrid laser-mig welding, *Journal of Materials Processing Technology* 191, 111-113.
- Chen, Y, Lei,Z, Li,L, Wu,L, 2006. Experimental study on welding characteristics of CO₂ laser TIG hybrid welding process, *Science and Technology of Welding & Joining* 11, 403-411.
- El-Batahy, A, 1997. Effect of laser welding parameters on fusion zone shape and solidification structure of austenitic stainless steels, *Materials Letters* 32, 155-163.
- Eriksson, I, Powell,J, Kaplan,A, 2011. Measurements of fluid flow on keyhole front during laser welding, *Science and Technology of Welding and Joining* 16, 636-641.
- Frostevarg, J, Kaplan,AFH, Lamas,J, 2013. Comparison of CMT with other arc modes for laser arc hybrid welding of 7 mm steel, 66th International Institute of Welding's (IIW) International Conference. Essen, Germany, .
- Kaplan, AFH, Nilsson,K, Powell,J, 2007. Shaping of hybrid welds and gap sensitivity, *Lasers in Manufacturing*. Munich, Germany, .
- Karlsson, J, Markmann,C, Minhaj Alam,M, Kaplan,AF, 2010. Parameter influence on the laser weld geometry documented by the Matrix Flow Chart, *Physics Procedia* 5, 183-192.
- Karlsson, J, Norman,P, Kaplan,AFH, Rubin,P, Lamas,J, Yañez,A, 2011. Observation of the mechanisms causing two kinds of undercut during laser hybrid arc welding, *Applied Surface Science* 257, 7501-7506.
- Kutsuna, M, Chen,L, 2003. Interaction of both plasmas in CO₂ Laser-MAG hybrid welding of carbon steel, *LAMP 2002: International Congress on Laser Advanced Materials Processing*.
- Lamas, J, Karlsson,J, Powell,J, Kaplan,A, F. H., Yañez,A, 2013. The effect of fit-up geometry on melt flow and weld quality in laser hybrid welding, *Journal of Laser Applications* 25, 7.
- Legodi, MA, de Waal,D, 2007. The preparation of magnetite, goethite, hematite and maghemite of pigment quality from mill scale iron waste, *Dyes and Pigments* 74, 161-168.
- Mendez, PF, Eagar,TW, 2003. Penetration and defect formation in high current arc welding, *Welding Journal* 82, 296-306.
- Nguyen, NT, Wahab,MA, 1996a. The effect of undercut and residual stresses on fatigue behaviour of misaligned butt joints, *Engineering Fracture Mechanics* 55, 453-469.
- Nguyen, TN, Wahab,MA, 1998. The effect of weld geometry and residual stresses on the fatigue of welded joints under combined loading, *Journal of Materials Processing Technology* 77, 201-208.
- Nguyen, TC, Weckman,DC, Johnson,DA, Kerr,HW, 2006. High speed fusion weld bead defects, *Science and Technology of Welding and Joining* 11, 618-633.
- Norman, PM, Karlsson,J, Kaplan,AF, 2011. Mechanisms forming undercuts during laser hybrid arc welding, *Physics Procedia* 12, 201-207.
- Otegui, JL, Kerr,HW, Burns,DJ, Mohaupt,UH, 1989. Fatigue crack initiation from defects at weld toes in steel, *International Journal of Pressure Vessels and Piping* 38, 385-417.
- Pengfei, H, Chao,T, Zhenyang,L, 2011. Fundamental research on the mechanism of high speed welding undercut, *Advanced Materials Research* 290, 2152-2155.
- Soderstrom, E, Mendez,P, 2006. Humping mechanisms present in high speed welding, *Science and Technology of Welding and Joining* 11, 572-579.
- Stauffer, H, 2005. Laser hybrid welding and laser brazing: State of the art in technology an practice by the examples of the Audi A8 and VW-Phaeton, München, .
- Sun, Z, Pan,D, Wei,J, 2002. Comparative evaluation of tungsten inert gas and laser welding of AZ31 magnesium alloy, *Science and Technology of Welding & Joining* 7, 343-351.
- Tani, G, Campana,G, Fortunato,A, Ascari,A, 2007. The influence of shielding gas in hybrid LASER-MIG welding, *Applied Surface Science* 253, 8050-8053.
- Tusek, J, Suban,M, 1999. Hybrid welding with arc and laser beam, *Science and Technology of Welding & Joining* 4, 308-311.
- Wieschemann, A, Kelle,H, Diltthey,D, 2003. Hybrid-welding and the HYDRA MAG LASER processes in shipbuilding, *Welding international* 17, 761-766.
- Zhu, J, Li,L, Liu,Z, 2005. CO₂ and diode laser welding of AZ31 magnesium alloy, *Applied Surface Science* 247, 300-306.